Multiwavelength follow-up of a rare IceCube neutrino multiplet

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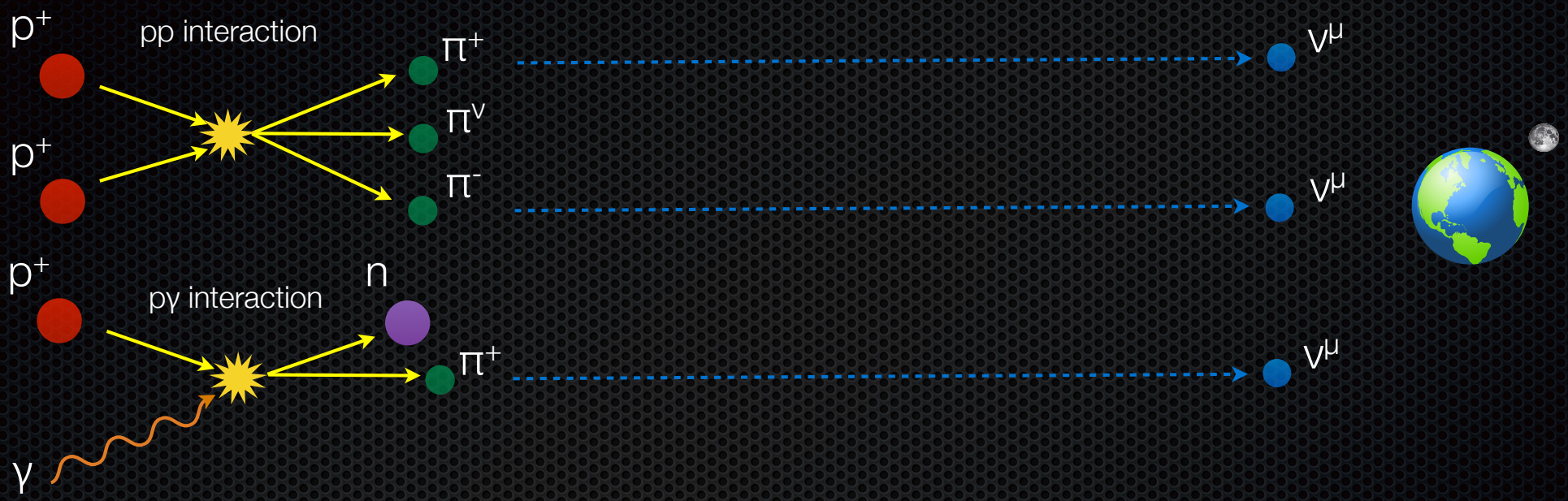
Paper Motivation

- IceCube detected three neutrino-induced track events arriving within less than 100s from a similar direction
- Expected chance occurrence rate of 1 every 14 years, so not exceptionally rare, but interesting
- If astrophysical in nature, the source would have to be relatively nearby or be an exceptional bright neutrino emitter
- Followup observations by Swift-BAT, Swift-XRT, Master, ASAS-SN, LCOG, Veritas, FACT, and HAWC
- The IceCube collaboration wanted to produce a paper summarizing the non-detections and outlining the followup network they have assembled
- We were asked by Anna Franckowiak to contribute Fermi analysis to their writeup of this event

IceCube Detection Review



- IceCube detects a few hundred astrophysical neutrino candidates (>10 TeV) of equal flavor per year isotropically distribution across the sky
  - Implies that many have extragalactic origin
- Generated through pp and pγ interactions at sites of proton acceleration
- The usual suspects for cosmic ray acceleration: GRBs, CC SNe, and blazars

Possible Associations

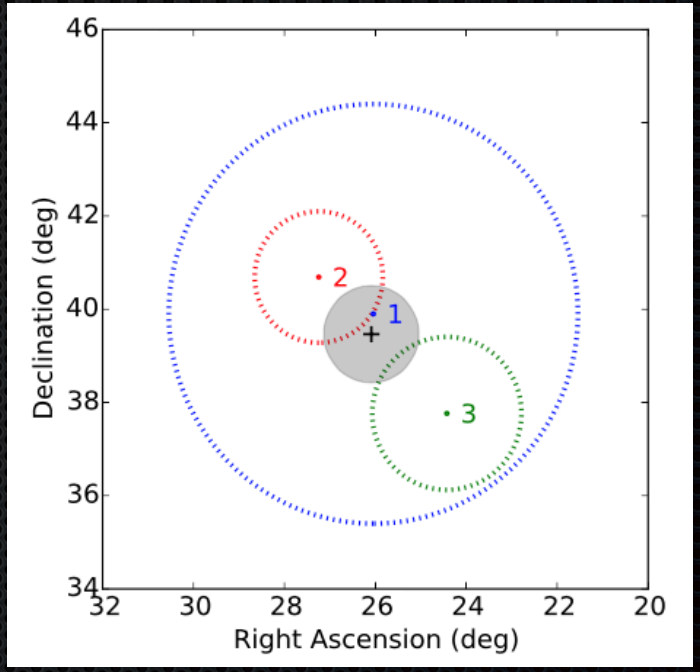
- SN Type IIn coincident with a neutrino doublet (Aartsen et al. 2015b)
  - Likely unrelated because it implies a huge neutrino luminosity
- Correlation between blazars and high energy neutrinos (Padovani et al. 2016)
- γ-ray outburst of a blazar was aligned with a PeV neutrino (Kadler et al. 2016)
  - Both blazar associations have a chance-coincidence probability of a few percent and are not considered highly significant
- GRBs can at most account for only 1% of the detected flux (Aartsen et al. 2015c)
- 2LAC blazars can contribute at most 27% of the detected flux (Aartsen et al. 2016c)
  - Non-detections imply neutrino flux must originate from a large number of faint neutrino sources (Murase & Waxman 2016)

Real Time Alerts

- Detections of high-energy neutrinos are now identified, reconstructed and reported promptly via GCN (Aartsen et al. 2016d)
  - Only select upward neutrinos for these alerts to reduce background
  - Hence they are only sensitive to sources in the Northern sky
- Real time search for neutrino clusters in time and space
  - Multiplets that arrive within 100s and within 3.5° on the sky
  - Also reported in real time via GCN
- Excellent sources to followup with X-ray and γ-ray instruments
  - $E_\nu > 1$ TeV ~ 1°
  - $E_\nu > 1$ PeV ~ 0.25°

IceCube Triplet Detection

- In Feb 2016, three neutrino-induced track events arriving within 100s
- E = 0.26 TeV, 1.1 TeV, & 0.52 TeV
- All three neutrinos are upward-going
- Did not pass the sky direction cut (3.5°) and was not issued in real time
  - Informed partners at T0+22hr
  - Normally ~3 min latency is expected
- Error = 1° (50%) & 3.6° (90%)
- Expected occurrence rate of 1 in 14 yrs



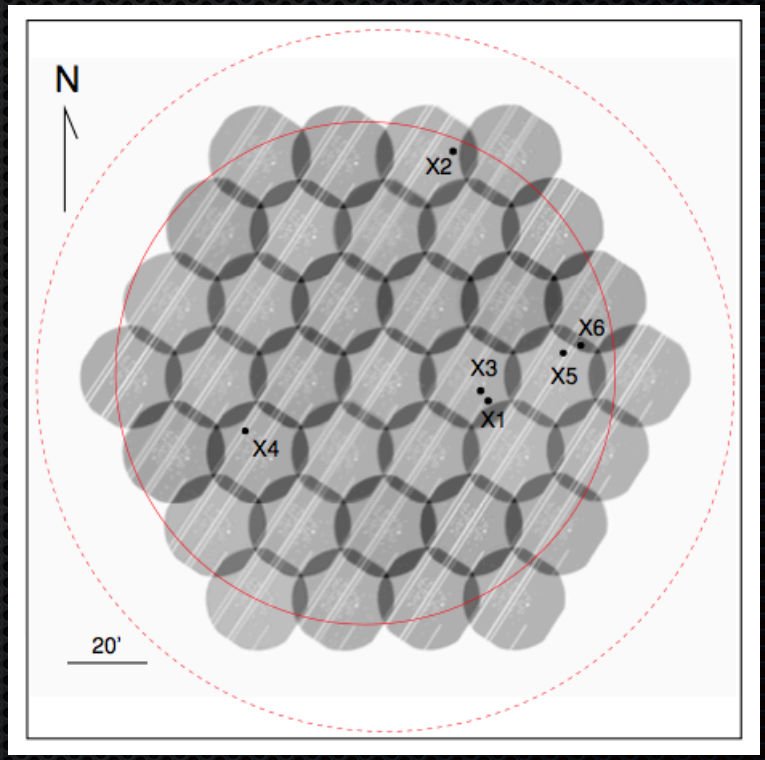

```
Date = 2016-02-17
Time = 19:21:31.65
MET = 477429695.650
RA = 26.1
Dec = 39.5
Error = 1.0 (50%), 3.6 (90%)
gall = 133.9392
galb = -22.2371
```

Triplet Followup Observations

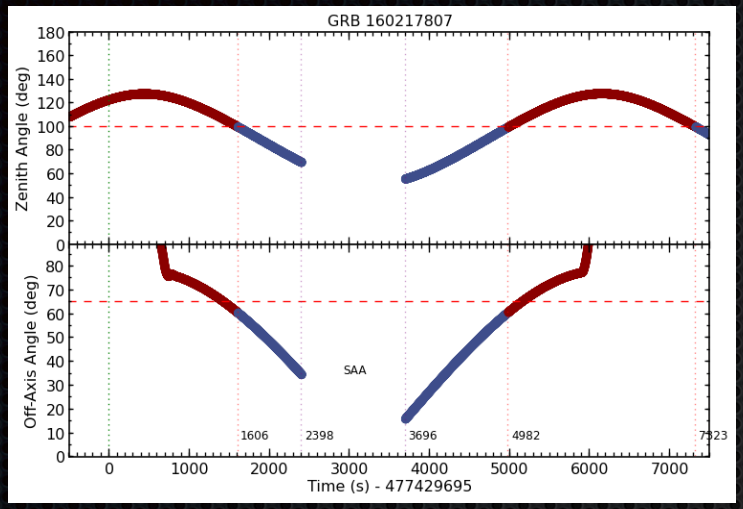
- The triplet position was ~70° of the sun
  - Difficult to observe with ground based observatories
  - Only observable at high-airmass near sunset
- Explicitly searched for GRBs, CCSNe, and AGN flares
- Instruments involved include:
  - Optical: ASAS-SN, MASTER, LCOGT
  - X-ray: Swift-XRT
  - γ-ray: Swift-BAT, Fermi-LAT
  - VHE: Vertias, HAWC

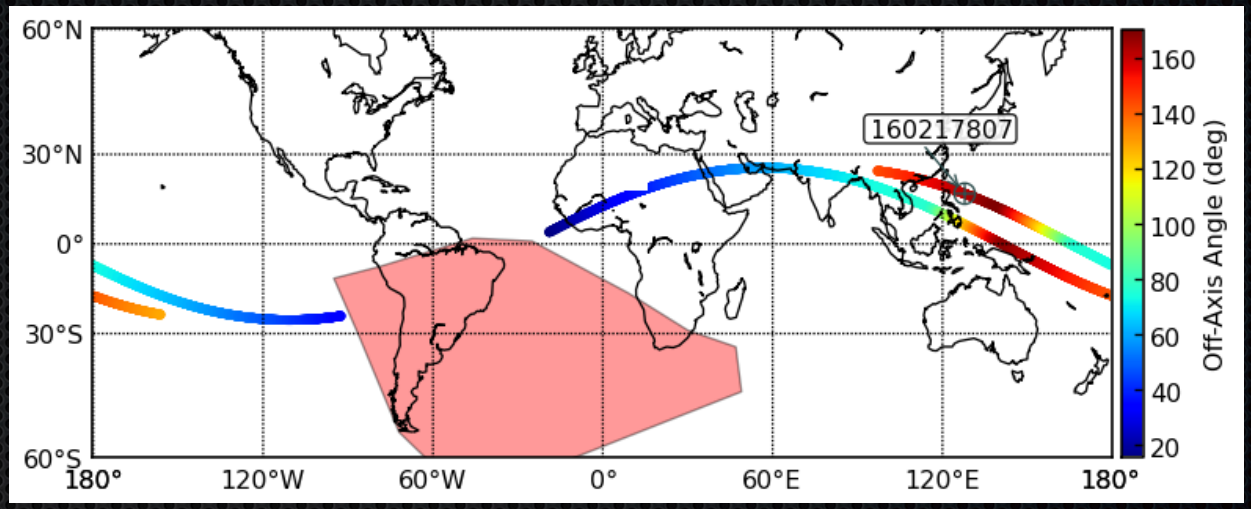
Swift Observations

- Triplet location was in the BAT FOV at T0+30s (by chance)
  - No rate or image trigger transients
- Requested a 37-pointing XRT ToO at T0+22.6h to cover the 50% localization
  - 0.3–0.4 ks per pointing
- Six x-ray sources were identified
  - 4 nearby stars and 2 AGN
  - Neither AGN show short term variability



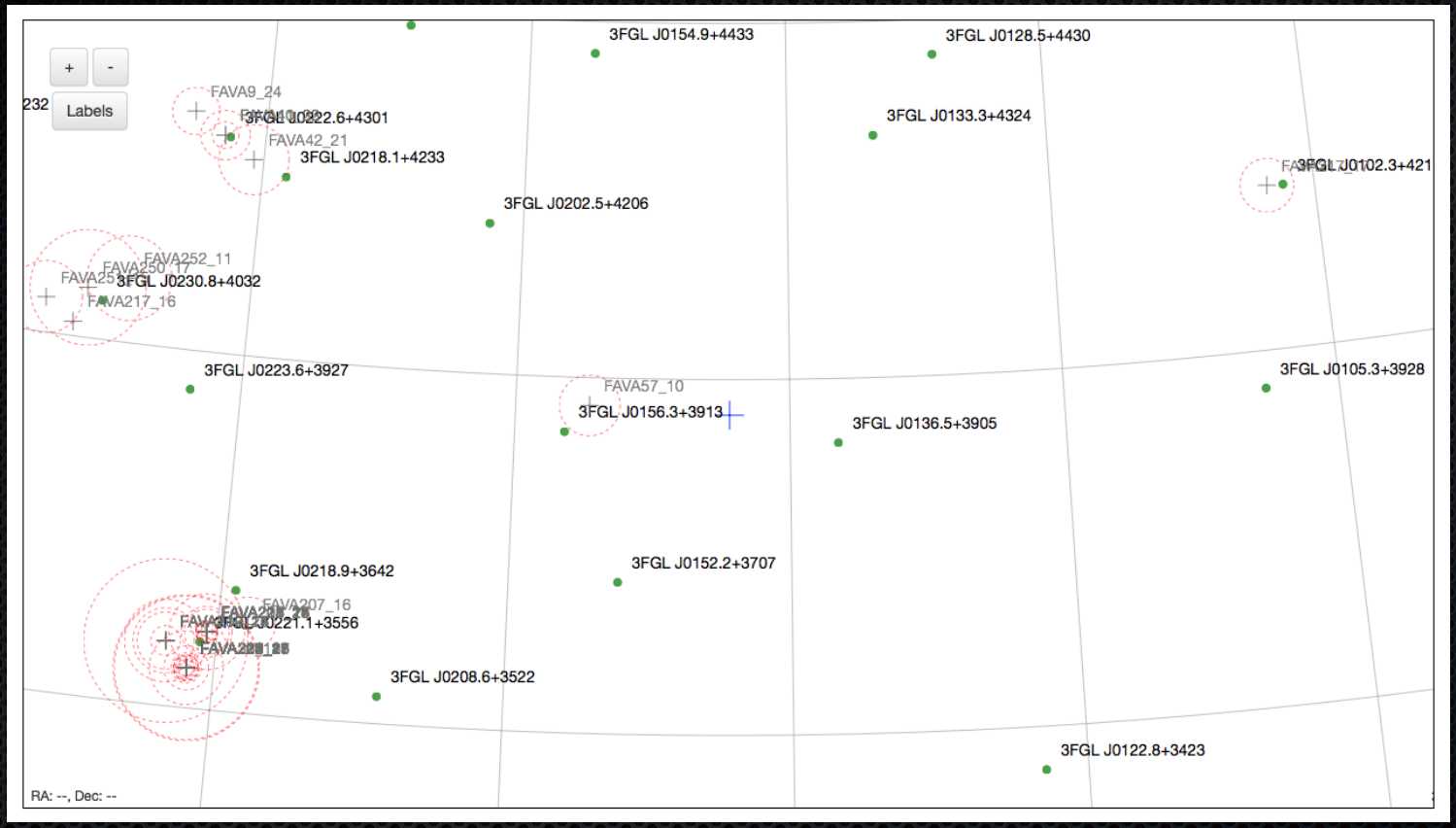
Fermi Observability





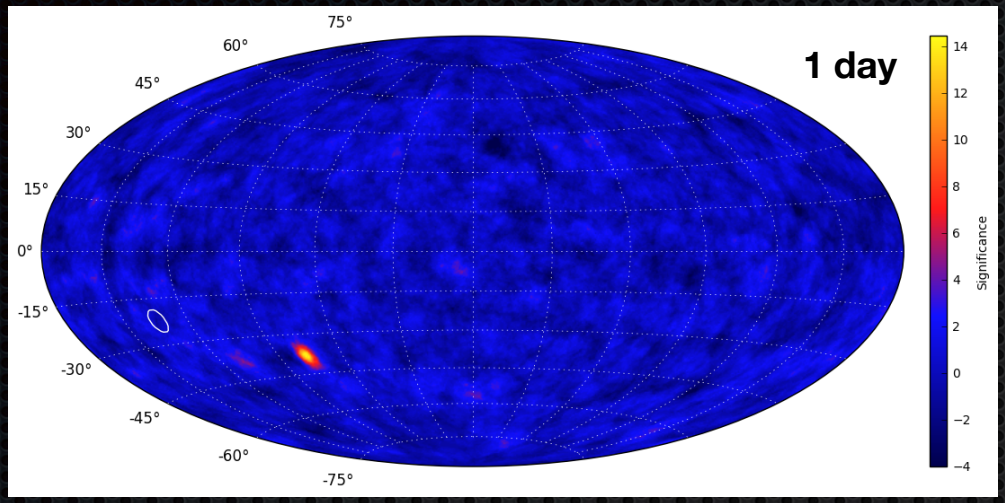
- The triplet position was occulted at the detection time of the first neutrino (T0)
- The triplet position does not enter the Fermi-LAT field of view (zenith<100, theta<65) until T0+1606 sec
- The GBM and LAT can place no constraints on the existence of a prompt gamma-ray transient coincident, so we search for extended emission on longer timescales

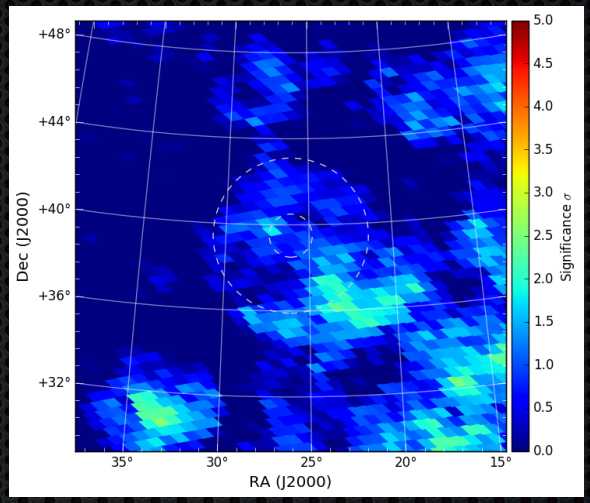
2FAV Search

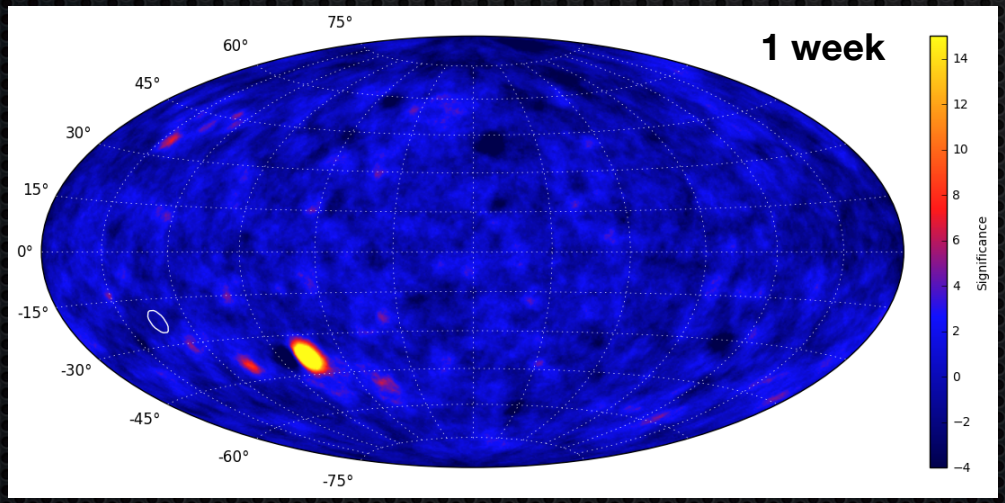


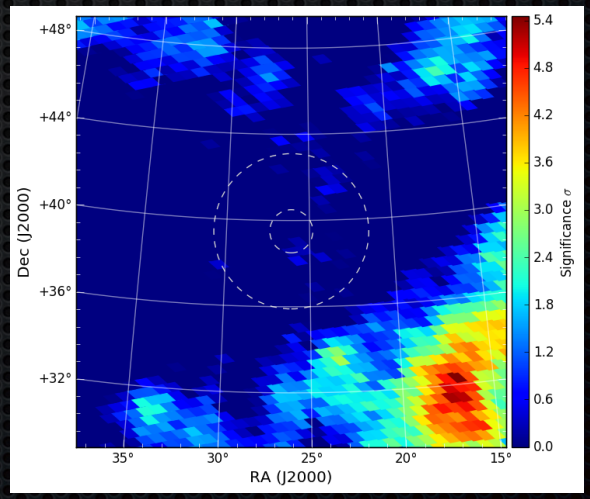
- The triplet location is a relatively quiet region of the gamma-ray sky. FAVA has detected only one week timescale flare from this region during the 10th week of the mission. Closest 3FGL source is known blazer

Dedicated FAVA Search





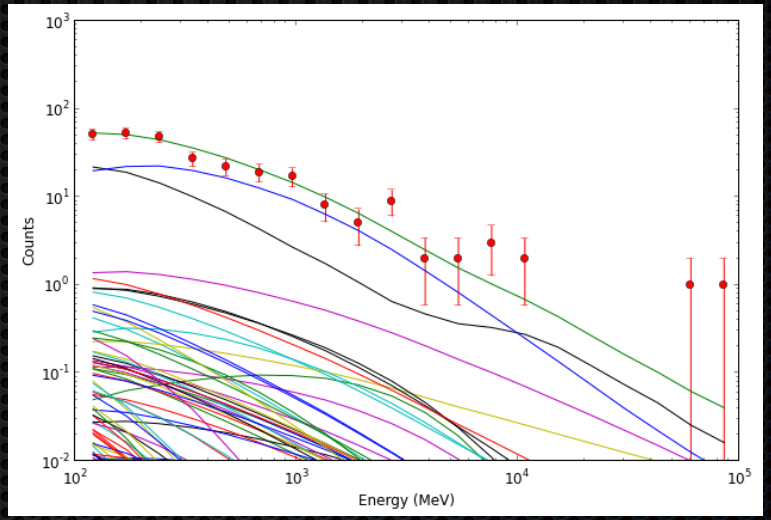


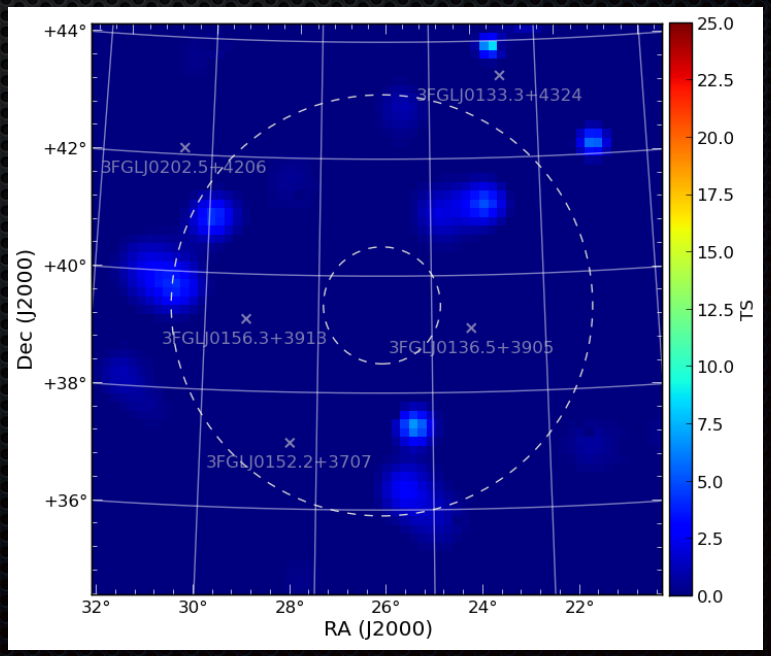


- Performed a FAVA search for a variety of timescales, including a 24 hour analysis bracketing T0 (T0+24h, T0-24h, and T0-12h) and a week long analysis. Found no significance transient sources

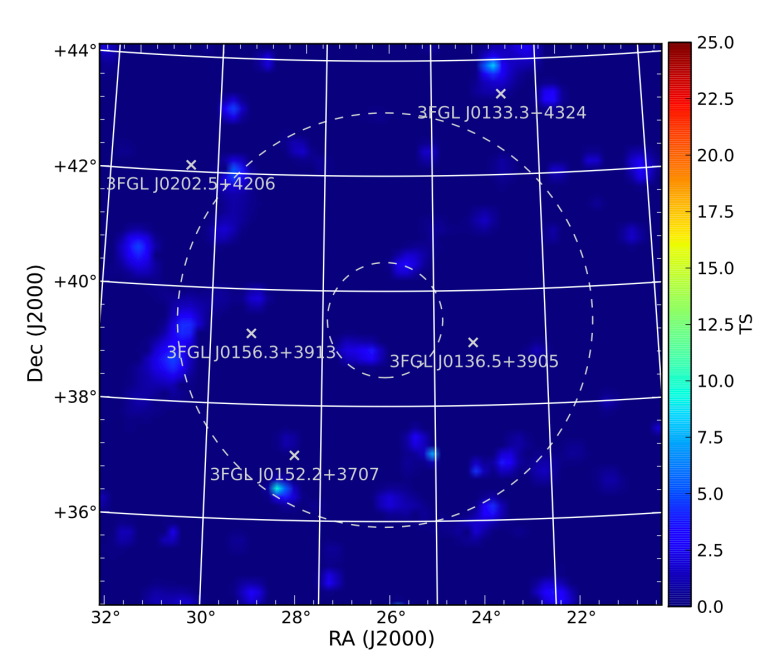
TS Map Analysis

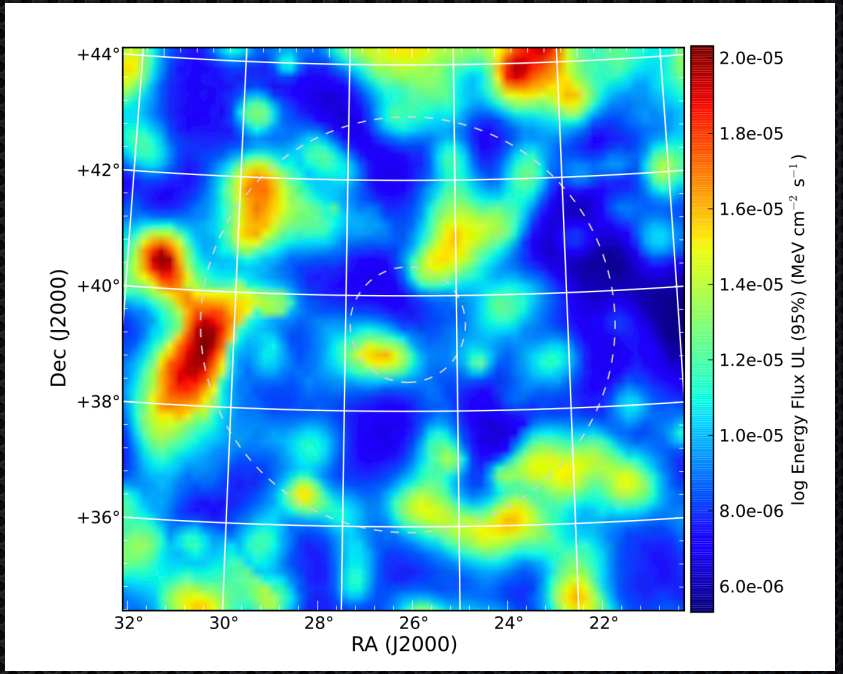
- Performed a likelihood analysis of the region over a coordinate grid on a variety of timescales
  - 10x10 deg with 0.15 deg binning
- Used the results of the analysis to produce TS and upper limit maps
- Likelihood fit parameters:
  - Energy: 100 MeV to 1e5 MeV
  - ROI & Zenith Cut: 12 deg, 90 deg
  - IRF = P8R2_TRANSIENT020_V6
  - All sources fixed to their 3FGL values





TS and Upper Limit Maps



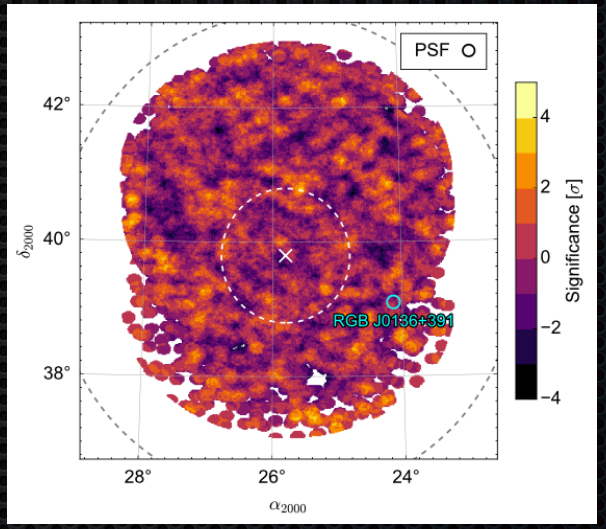


- We produced TS and upper limit maps for a variety of timescales
  - T0+/-6h, T0+/-12h, T0+/-24h, & T0+14dy
- We calculated the median upper limit for each interval
- The 14 day analysis TS and UL maps appear in the paper

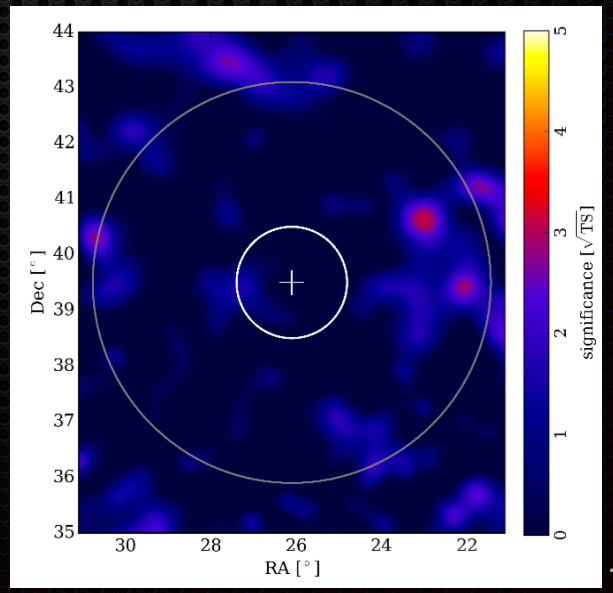
VHE Observations

- Veritas
  - Covered 80 GeV to 30 TeV
  - Observations began T0+8 days because of moon constraints
  - VHE source 3FGL J0136.5+3905 is within the 50% error region, but was not detected
- HAWC
  - Covered 100 GeV and 100 TeV
  - Triplet position was in the HAWC FOV at T0
  - Observations consistent with expected background
- No new gamma-ray sources detected by either observatory

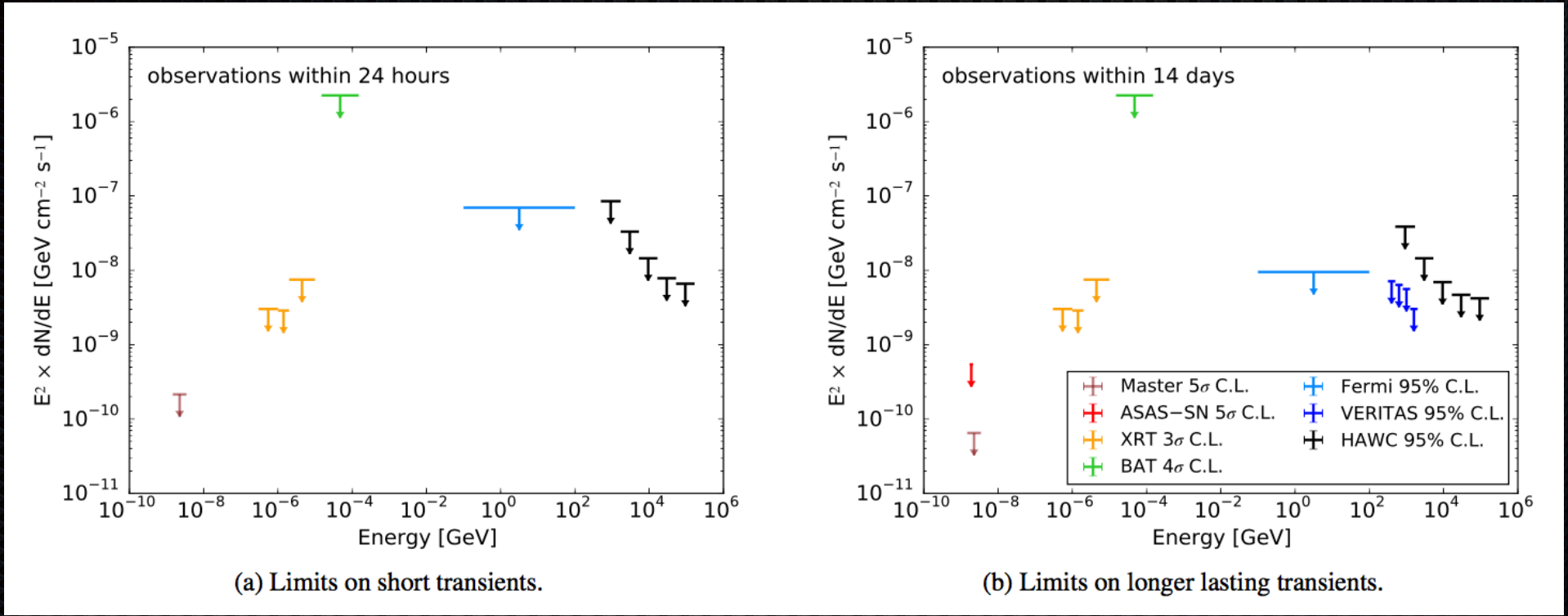
Veritas



HAWC



Observation Summary



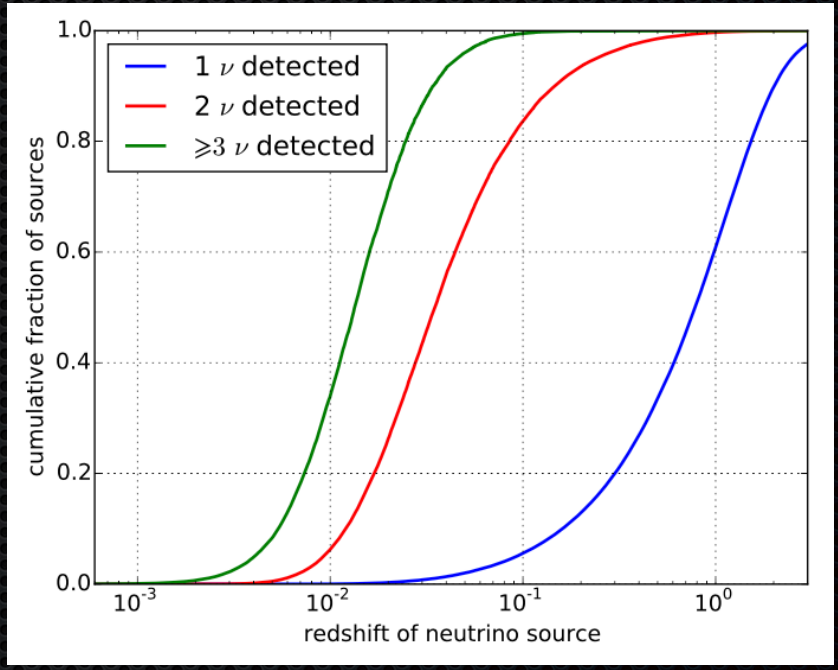
(a) Limits on short transients.

(b) Limits on longer lasting transients.

- 24 hour and 14 day upper limits
- Note that the upper limits use a variety of confidence levels and spectral indices

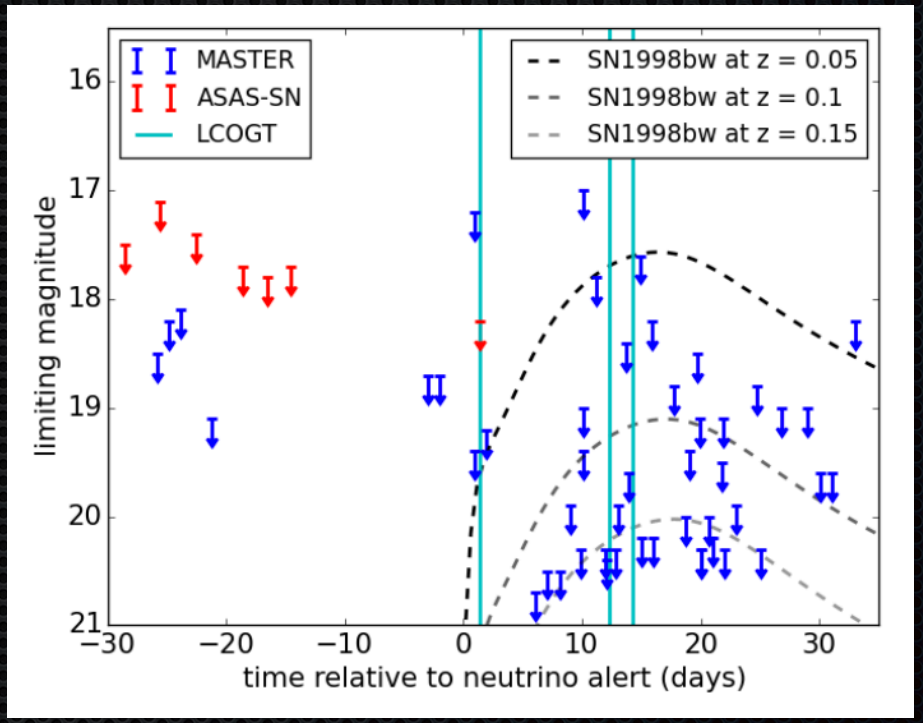
Neutrino Source Population

- We can quantify the likeliest distance of the triplet source by simulating a population of neutrino emitters
  - Density: 6×10^{-6} Mpc^{-3} yr^{-1} (5% CCSN)
  - Energy: $E^{-2.5}$, Redshift: SFR
- Liso distribution assumed to be 1 dex
- IceCube observations set an upper limit on the total allowable flux
- Detecting 3 neutrinos from the same source requires it to be relatively nearby
- Median redshift of a >10 TeV triplet source is $z \sim 0.04$

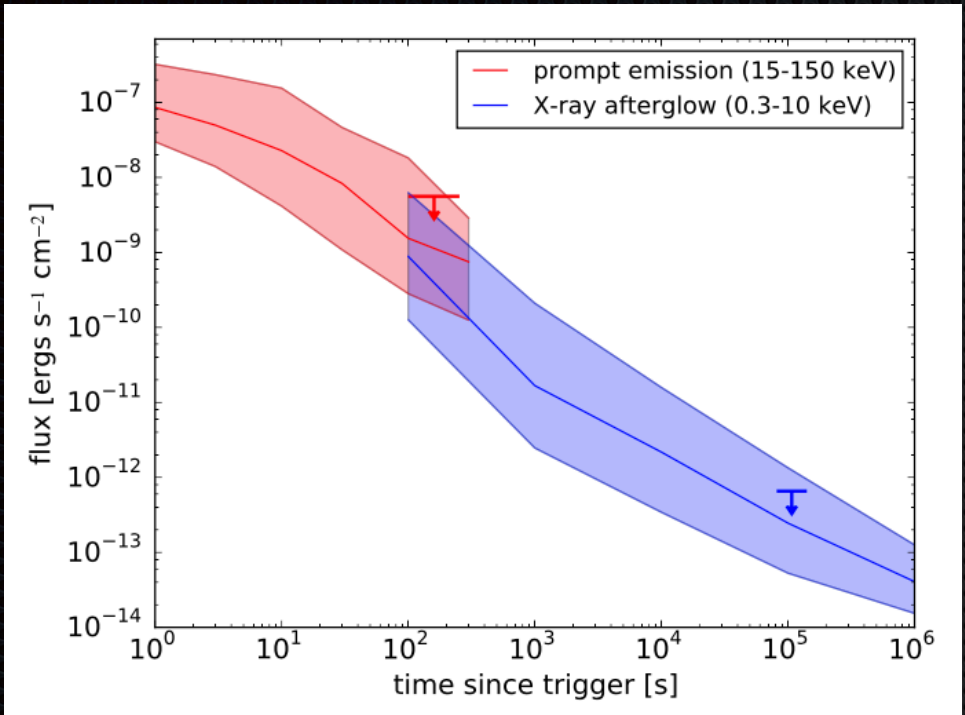


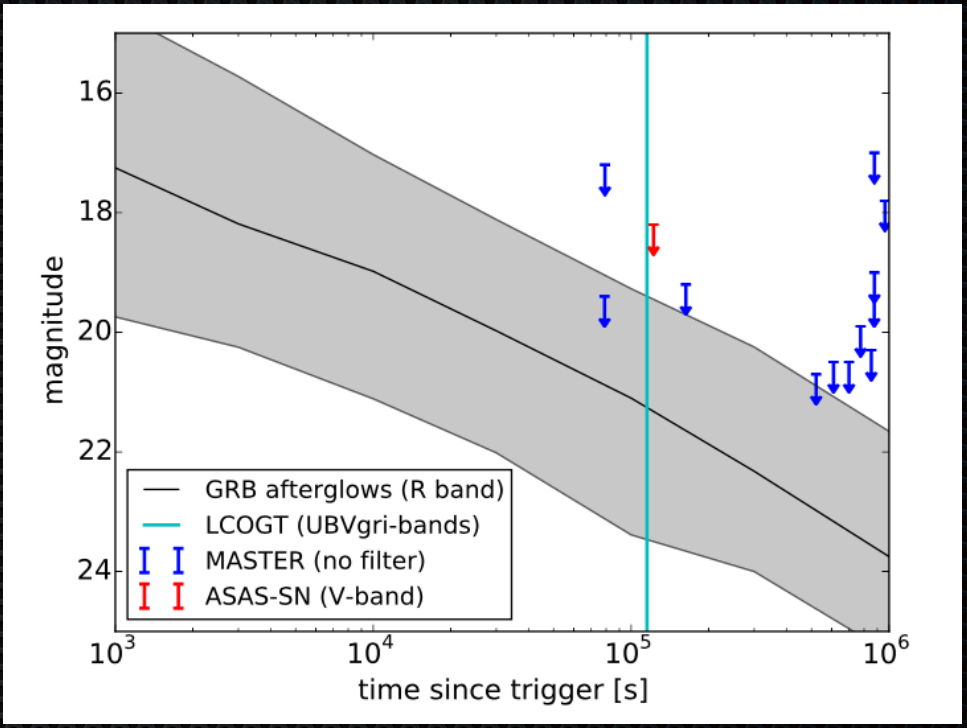
CC SNe Association

- Upper limits derived from the optical observations before and after T0
- Compared to the light curve of the bright Type Ic broadlined SN 1998bw which accompanied GRB 980425
- A similar supernova would be detectable out to $z \sim 0.15$
- We can rule out an SN similar to the previous Type IIn SN association
- Any SN would have to have been unusually dim or heavily obscured



GRB Association





- Prompt BAT, XRT, and optical limits were compared to the distribution of detected γ-ray, X-ray, and optical light curves
- A brighter-than-average GRB should have been detected by Swift, although a burst at z ~ 0.04 would have been detected unless it was under-luminous
- No GRB was detected by any of the IPN spacecraft, so unlikely a GRB

AGN Association

- XRT detected two AGN, but neither show any short term variability
- No flaring activity detected by LAT, Veritas, or HAWC
- The three 3FGL source within the 90% error do not show any activity before or after the trigger
- 3FGL J0156.3+3913 flared once in 2009
- 3FGL J0136.5+3905 is a VHE, but undetected by Veritas
- We conclude that there was no AGN activity coincident with the triplet detection
- It remains unclear if an AGN flare below the derived limits can yield a large neutrino flux

Conclusions

- IceCube detected three ~1 TeV neutrino-induced track events arriving within less than 100s from a similar direction
- Expected chance occurrence rate of 1 every 14 years, so its possible this was due to a background fluctuation
- If astrophysical in nature, the source would have to be relatively nearby or be an exceptional bright neutrino emitter
- A nearby broad-lined CC SNe and/or GRB seem as unlikely origin and no evidence of coincident AGN flaring activity
- Prompt followup observations of future multiplet events may be the best candidates with which to constrain neutrino sources because their origin should be relatively nearby

Paper Status

- Cat 2 paper lead by IceCube collaboration with a Fermi author block
  - Lead author is Nora Linn Strotjohann (nora.linn.strotjohann@desy.de)
- Judy Racusin served as the LAT internal reviewer
- Results are summarized on confluence here:
  - https://confluence.slac.stanford.edu/display/SCIGRPS/Fermi-LAT+Followup+of+IceCube+Triplet+Neutrino+Eventx
- Latest Draft:
  - https://www-glast.stanford.edu/cgi-prot/pub_download?id=1368